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Report
Poreh

STATISTICAL PROPERTIES AND SIMILARITY OF LINE INTEGRATED CONCENTRATION FLUCTUATIONS ACROSS PLUMES DIFFUSING IN GRID-GENERATED TURBULENCE

by
M. Poreh & J.E. Cermak

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MEMORANDUM

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DATE: 24 September 1993

SUBJECT: Fluctuations of Concentration Line Integrals on Paths Through Aerosol Plumes; CSU Project 5-3 8765

Enclosed please find the report entitled "Statistical Properties and Similarity of Line Integrated Concentration Fluctuations Across Plumes Diffusing in Grid-generated Turbulence" by M. Poreh and J. E. Cermak.

This completes our obligations under this current funding. Please call if you have any questions.

JEC:gg
Enclosure
c: M. Poreh
G. Rubel, CRDEC
E. Steubing, CRDEC
c:letter only: K. Delehoy, CSU, OSP

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STATISTICAL PROPERTIES AND SIMILARITY OF LINE INTEGRATED CONCENTRATION FLUCTUATIONS ACROSS PLUMES DIFFUSING IN GRID-GENERATED TURBULENCE

by

M. Poreh and J. E. Cermak

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FINAL REPORT for

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ABSTRACT

Measurements of integrated concentration (IC) across a plume diffusing in a turbulent flow generated by a 35.6 cm grid were made at close distances to the source, $2 \leq x/M \leq 17$, where x is the distance from the point source and M the mesh size of the grid. Analysis of these and previously measured data at $20 \leq x/M \leq 100$ downwind of a 7.6 cm grid, shows that the statistical properties of the IC fluctuations close to the source are primarily controlled by the meandering of the plume and are basically different from those measured at large distances from the source. It is also shown that these statistical properties rapidly approach an approximately similar distribution as the plume is transported downwind: The mean lateral distributions of the mean values of IC are shown to be Gaussian, starting at $x/M = 2$. The measured lateral distribution of the relative rms values of IC at all distances are also similar to each other, namely are functions of y/σ, where $\sigma(x)$ is the lateral length scale of the mean plume and y is the lateral distance from the axis of the plume, and independent of x. The autocorrelation of IC fluctuations appears to become similar at approximately $x/M = 4$, whereas the probabilities $P(a)$ that the ratio of the instantaneous values of IC to the mean value of IC at each point exceeds a given value a, the rms/mean ratio of the fluctuations and the lateral distribution of the intermittencies of the fluctuations become approximately similar around $x/M = 20$. The physical basis for the observed similarity is discussed.

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1.0 INTRODUCTION

In recent years there has been a growing interest in concentration fluctuations. While most researchers have investigated the properties of concentration fluctuations at a point, interest in the dynamical nature of obscuration by aerosol plumes have led the authors to undertake a series of systematic studies on the nature of line integrated concentration fluctuations across plumes from point sources diffusing in boundary layer shear flows and in grid-generated turbulence. Using a fast response Infrared/Carbon Dioxide (IR/CO_2) system, which can measure integrated concentrations across wind-tunnel plumes, the statistical characteristics of these fluctuations for a variety of boundary conditions have been measured and analyzed by the authors, see References.

The first IR/CO_2 system (Fig. 1.1) was used to study the fluctuations of Vertically Integrated Concentrations (VIC) across plumes from ground-level sources diffusing in a simulated Atmospheric Surface Layer (ASL) at the Technion Environmental Wind Tunnel in Haifa, Israel (Poreh and Cermak, 1987). Perhaps the most striking finding of that investigation has been an observed approximate similarity of the statistical properties of the fluctuations, when expressed as a dimensionless function of the source strength Q, the boundary-layer thickness δ, the mean velocity at $z = \delta$, and the lateral length parameter of the mean plume σ. Namely, it was found in the study that

$$VIC^* = (VIC)\, U\delta/Q = F\,(y/\sigma)$$

and is approximately independent of the distance x from the source.

Measurements of VIC^* were made along the centerline of the mean plume, $y/\sigma = 0$, for the range $x/\delta = 0.8 - 2.2$ in that wind tunnel. Figure 1.2 describes the measured probability

$P(a)$ that the instantaneous value of VIC^* at a point is larger than a times its mean value $VICM^*$ at that point. Since the mean value of VIC^* can be estimated using classical mean plume models, such a similarity is of great help in predicting the probability of the occurrence of large instantaneous values.

Our surprise from the observed similarity stemmed from theoretical considerations which suggest that both the effect of the shear and the relative growth of the plume with the distance would be to attenuate the concentration fluctuations. Thus, the observed similarity was partially attributed to the lack of accuracy of the original IR/CO_2 system, which is apparent in Fig. 1.2.

Repeated measurements of VIC fluctuations in a thick boundary layer flow, $\delta = 1.0$ m, at the Meteorological Wind Tunnel in Colorado State University, using a refined IR/CO_2 system (Poreh and Cermak, 1988, 1990d) have indeed shown a very small but consistent attenuation of the VIC fluctuations and thus a small change of the shape of $P(a)$ with distance, as demonstrated in Fig. 1.3. However, for all practical purposes, the existence of an approximate similarity in the range $0.3 < x/\delta < 2.5$ have been reconfirmed in these experiments. This range of x/δ, it should be noted, corresponds to values of 200 m to approximately 2000 m for x in the atmospheric boundary layer, whose mean thickness is of the order of 600 m. The solid line in this figure is from an approximate semiempirical model for predicting the VIC fluctuations by Poreh and Cermak (1990a).

Measurements of VIC fluctuations in a $\delta = 0.25$ m boundary layer over a rough surface, which simulate flow over a suburban area (Poreh et al., 1991e) in the range $1 \leq x/\sigma \leq 9$, see Fig. 1.4, have, however, confirmed our expectations that the previously observed approximate similarity found in shear flows is limited to intermediate distances from the source, and that the

effect of shear and relative growth of the plume size is to slowly attenuate concentration fluctuations at large distances from the source, particularly for rough surfaces.

To develop a better understanding of the dynamics of concentration fluctuations, measurements were made of Integrated Concentrations (IC) across a plume diffusing in grid-generated turbulence (Poreh et al., 1991f). Grid-generated turbulence is one of the simplest types of turbulent flows. When viewed by an observer who follows the mean motion, the turbulence field in the neighborhood of a point appears to be closely homogeneous, and its decay rate is relatively small. For these reasons it has been extensively used in basic studies of turbulence and diffusion in turbulent flows.

Measurements of IC were made downwind of two grids. Initially, (Series I), a grid with M = 7.82 cm and porosity p = 0.56 has been used. Analysis of these measurements revealed that the data were affected by jet coalescence downwind of the grid, which has introduced some noise. The measurements in Series II were made downwind of a grid with larger porosity, p = 0.64 and M = 7.62 cm (7.6 cm), and a large improvement in the quality of the data was observed. Unless otherwise noted, data presented in this report are only data from Series II. The source in these series was located at $x_0/M = 20$ downwind of the grid.

Figure 1.5 shows the distributions of $P(a)$ along the centerline of a plume diffusing in grid-generated turbulence. The probability $P(a)$ denotes the probability that the instantaneous value of IC is larger than a time its mean.

In general, it is expected that for each realization the statistical properties of the IC fluctuations in such a flow would be a function of the dimensionless distance from the source x/M where M is the grid size. However, for this case too, we have found that in the range

$20 \leq x/M \leq 100$ the statistical properties of IC* = (IC) UM/Q depend primarily on y/σ, and practically independent of the distance, as shown in Fig. 1.5.

In addition to the approximate similar probability distribution functions at different distances, we have found that the spectral energy functions and autocorrelation functions at different distances were similar when nondimensionalized by the local value of σ.

What was more surprising was the resemblance of the various statistical properties of IC at different distances to those of VIC across plumes diffusing in boundary layers. Of course, in both cases these properties were slightly dependent on the distance, but as shown in Fig. 1.6, the measured PDF of the ratio of the instantaneous over the mean values in both cases were very close indeed.

As in the case of diffusion in shear flows, we expected the observed approximate similarity of the concentration fluctuations of plume diffusing in grid-generated turbulence to be limited to a short range of distances downwind of the source. Measurements in the range $20 < x/M < 100$ have not confirmed our expectations, however. We have, however, hypothesized that at closer distances from the source, large deviations from the observed similarity would be found.

The main goals of this investigation were, thus, to examine the above mentioned hypothesis, to further explore the existence of similarity of the statistical properties of integrated concentration fluctuations across plumes and to provide data for an extensive model of IC fluctuations at different distances from the source.

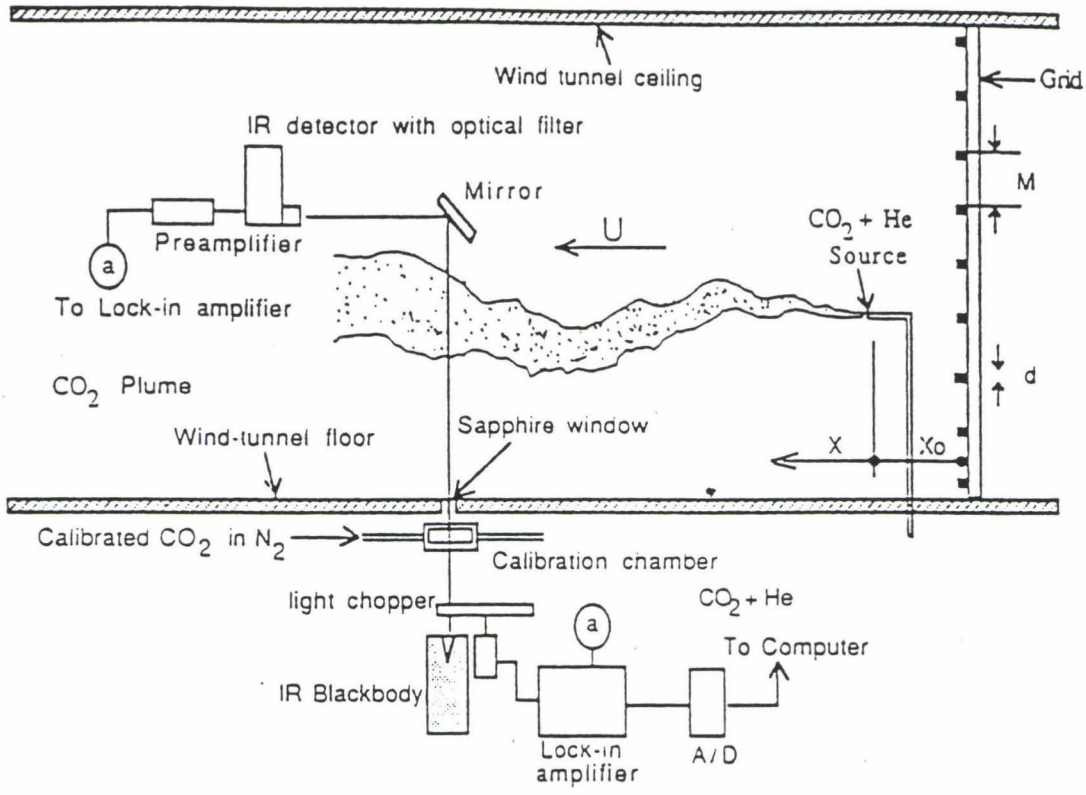

Fig. 1.1. Schematic description of the experimental system.

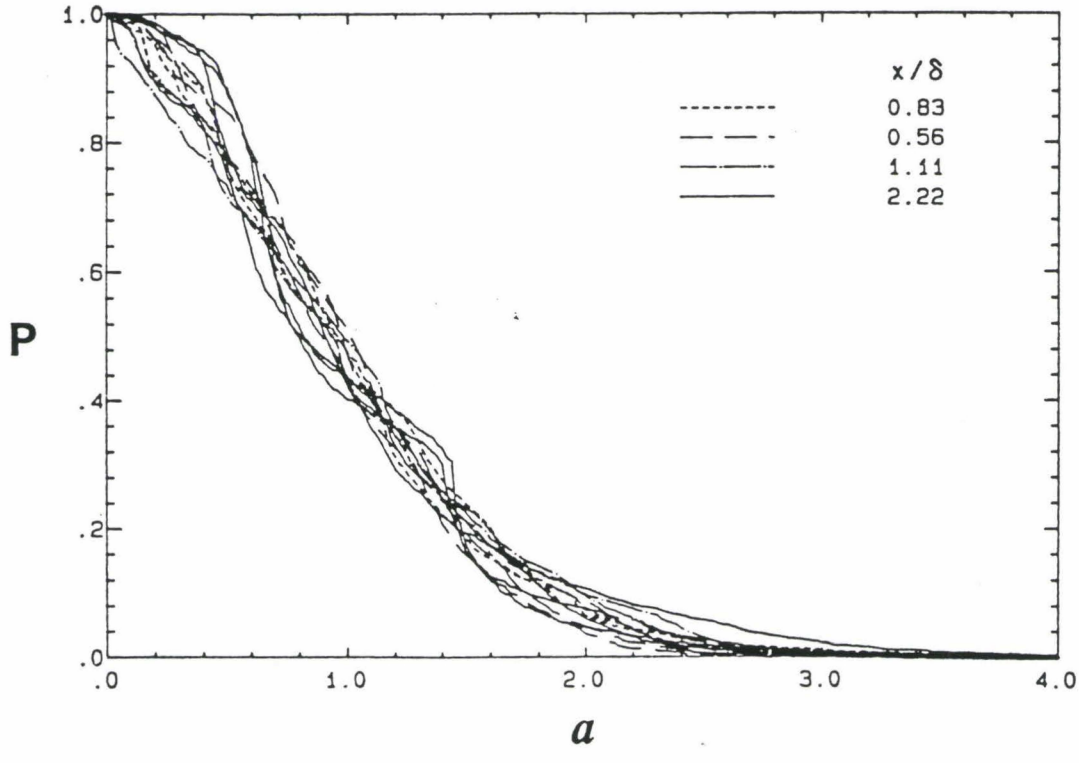

Fig. 1.2. The probability P(a) that VIC*/VICM* exceeds the value a along the centerline of a ground-level plume diffusing in a boundary layer over a smooth surface (Poreh and Cermak, 1987).

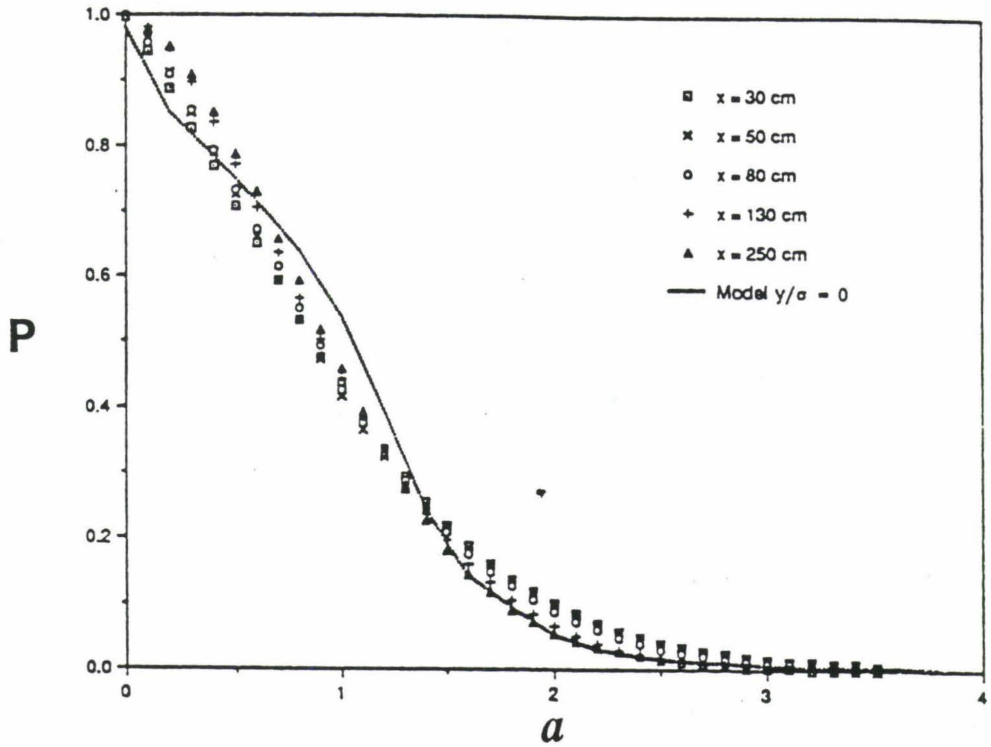

Fig. 1.3. The probability P(a) that VIC*/VICM* exceeds the value a near the centerline of a ground-level plume diffusing a boundary layer over a smooth surface. The solid line is a semi-empirical model (Poreh and Cermak, 1990a).

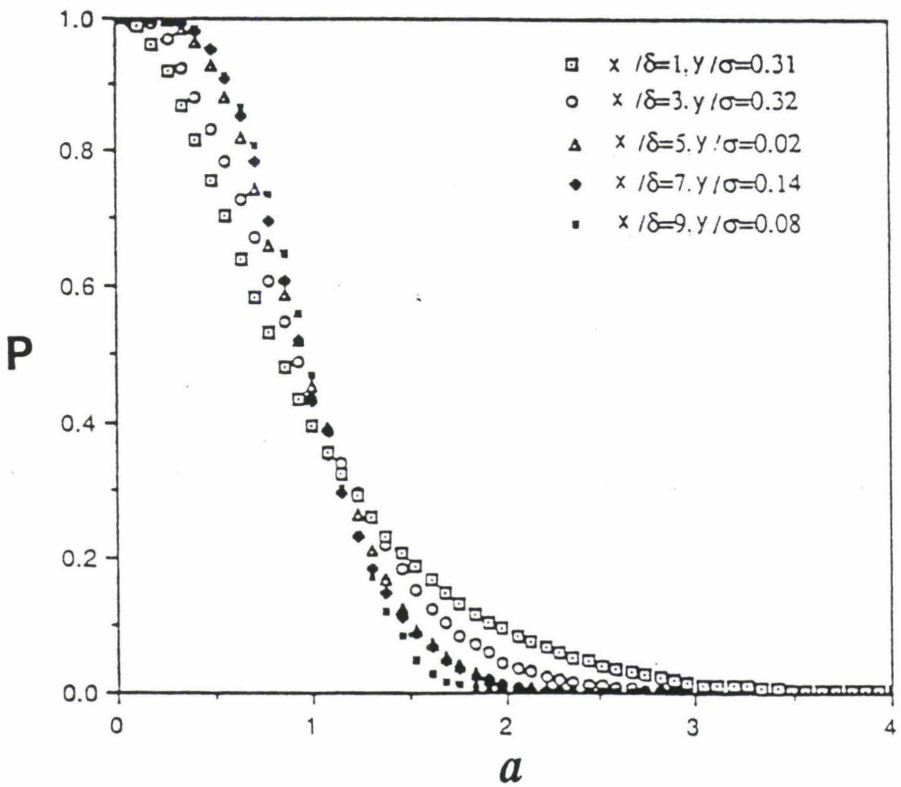

Fig. 1.4. The effect of the distance on P(a) near the centerline of a plume diffusing in a boundary layer over a rough surface.

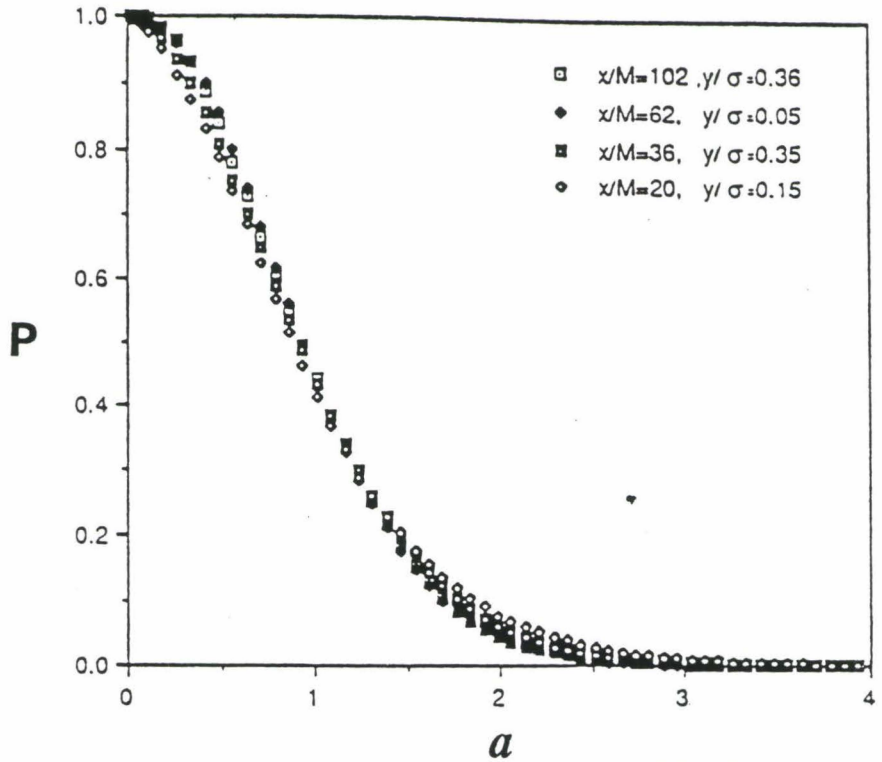

Fig. 1.5. Typical distributions of the probability P(a) that IC*/ICM* exceeds the value a measured near the centerline of a plume diffusing in grid-generated turbulence.

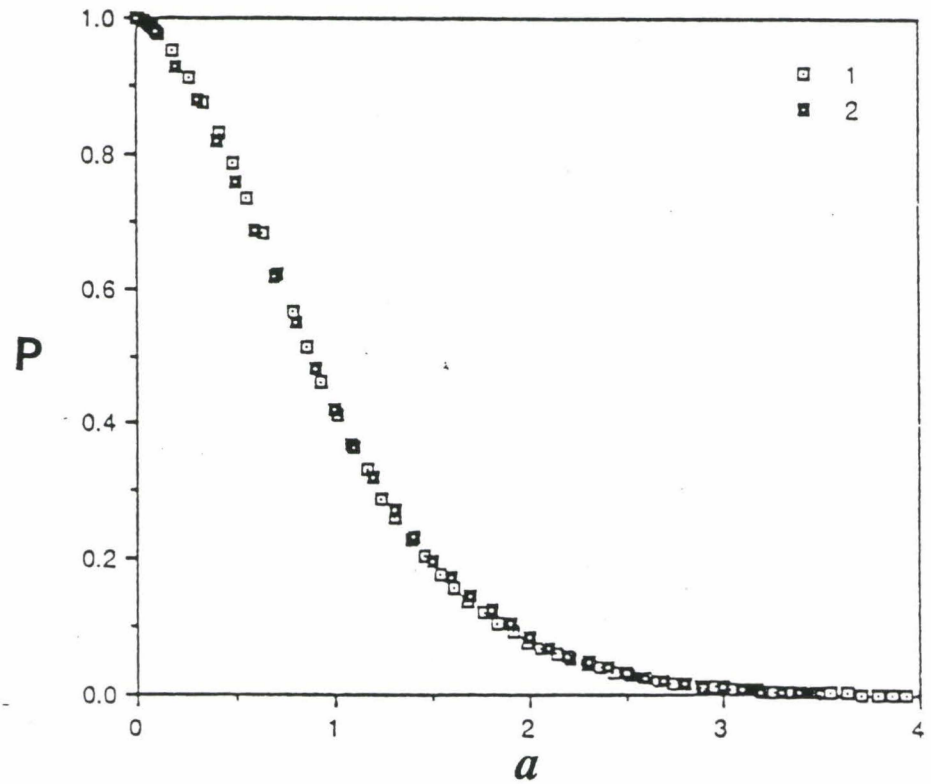

Fig. 1.6. Comparison of the distribution of P(a) of (1) IC*/ICM* for a plume diffusing in grid-generated turbulence (M = 7.62 cm, x/M = 20, y/σ = 0.15), and (2) the distribution of VIC*/VICM* for a ground-level plume diffusing in a smooth boundary layer flow (σ = 1.0 m, y/σ = 0.5, y/σ = 0.2).

2.0 THE EXPERIMENTAL SYSTEM AND PROCEDURES

The experiments were conducted at the Meteorological Wind Tunnel (MWT) at the Fluid Dynamics and Diffusion Laboratory at Colorado State University.

The wind-tunnel configuration and IR/CO_2 system were identical to those used in our previous studies (Poreh and Cermak, 1990d) except for the following changes:

1. Turbulent flow in the MWT was generated using an M = 35.6 cm grid. The grid was made of 2.54 cm x 0.64 cm bars and its porosity p was 0.646.
2. The source of the tracer gas for each realization was made from a brass tube which emitted the gas horizontally parallel to the mean flow. The diameter of the brass tubes used in the different experiments was changed according to the distance x from the source to the point of measurement; OD = 0.318, 0.318, 0.396, and 0.554 cm for measurements at x = 73.7, 149.9, 299.7, and 604.5 cm (x/M = 2.07, 4.215, 8.43 and 17), respectively.
3. The distance from the grid to the source was x_0 = 152.4 cm (x_0/M = 3.5). (Note that x_o/M = 20 in the experiments downwind of the 7.62 cm grid. Experimental limitations made it impossible to match these two dimensionless parameters.)
4. The diameter of the IR beam was 0.64 cm except for measurements at x = 73.7 cm, where a 0.32 cm beam was used.
5. The mean velocity in the tunnel was approximately 2.5 m/s.

3.0 PRESENTATION AND ANALYSIS OF THE MEASUREMENTS

For each run 16000 measurements of the integrated concentration (IC) were made at a sampling rate of 600/s, which were directly converted into dimensionless numbers

$$IC^* = (IC)\ UM/Q, \tag{3.1}$$

where Q is the strength of the source. The mean value of IC^*, designated by ICM^*, for each run was then calculated, so that the fluctuating value $ic^{*\prime}(t)$

$$ic^{*\prime}(t) = IC^*(t) - ICM^* \tag{3.2}$$

could be calculated. The rms value of $ic^*(t)$ will be denoted by $ic^{*\prime}$.

The lateral distributions of $ICM^*(y)$ at the different locations were found to be closely Gaussian:

$$ICM^*(y) = ICM^*(0)\ \exp\ [-y^2/(2\sigma^2)], \tag{3.3}$$

where $\sigma(x)$ is the lateral length scale of the mean plume. The values of $ICM^*(0)$ and σ at each distance were calculated so that the sum of the squares of the deviations from the Gaussian curve was minimum. The variation with x/M of $ICM^*(0)$, σ/M and the product $ICM^*(0)\sigma/M$ are shown in Fig. 3.1, together with the corresponding values from the previous experiments.

The differences between the absolute values of $ICM^*(0)$ and of σ in the three cases, are assumed to be due to the different shapes of the grids and the different values of the distances between the grids and the sources in the three cases. The products $ICM^*(0)\sigma/M$ in the three cases are close to $(2\pi)^{-1/2}$, however, as required by the continuity equation.

Typical variations of IC^* versus the dimensionless time $T^* = tU/M$, from the experiments downwind of the 7.6 cm and 35.6 cm grids, are shown in Figs. 3.2 through 3.4. Figure 3.2 shows the data at approximately the centerline of the plume. Figures 3.3 and 3.4

show the data at the edge of the plume, y/σ = O (1.5), and at the far edge y/σ = O (2.5). The mean and rms values for each run are shown on the right of the graphs. One clearly sees from the graphs that the time scale of the fluctuations increases with the distance from the source.

The probability distribution functions $P(a)$, which describe the probability that the ratio of the instantaneous value of IC to its mean is larger than a given value a, at different off-center locations are plotted in Figs. 3.5 through 3.8 for x/M = 2.07, 4.215, 8.43 and 17.0. We have omitted from the figures data points near $a = 0$ which had been affected by noise. As seen in the top graph of Fig. 3.5, the mean value of IC at that location was only 0.02, whereas the recorded peaks of IC were approximately 100 times larger than the mean value. The noise level in this and in similar cases was relatively high and it affected values of $P(a)$ up to values of a of the order of 1. Data at larger values of a were extrapolated to $a = 0$, by using a 3rd degree polynomial, which is plotted in these figures in solid lines. The intercept of the polynomial with $a = 0$ is equal, by definition, to the intermittency γ. As seen from Fig. 3.5, the intermittency at x/M = 2.07 and y/σ = 2.44 is of the order of 0.18.

Figures 3.9 through 3.11 show the effect of the relative distance x/M on $P(a)$ at different off-center locations. In these figures data from our previous measurements downwind of the 7.6 cm grid are included. One sees in Fig. 3.9, which shows the distribution of $P(a)$ at the centerline of the plume, a continuous change of the shape of $P(a)$ with distance from the source, which implies that the IC fluctuations at different distances are <u>not similar</u> at all. However, it is also observed from this figure that the effect of the distance on $P(a)$ at large distances from the source, the effect of the distance becomes milder and the $P(a)$ curves at x/M = 36 and at x/M = 102 are very close to each other. For this reason we have concluded earlier that at this range the IC fluctuations are approximately similar. A similar effect of the

distance is observed in Fig. 3.10 and in Fig. 3.11 which show the measured distribution of $P(a)$ at close dimensionless off-center locations.

The distributions of the relative rms values of the fluctuations of the integrated concentrations, $ic^{*\prime}(y/\sigma)/ic^{*\prime}(0)$, at different distances from the source are shown in Fig. 3.12. A comparison between these data and those measured downwind of the 7.6 cm grid is presented in Fig. 3.13. The data exhibit a close similarity of the relative rms values, in spite of the fact that the PDFs of the fluctuations are not similar.

Figure 3.14 show the distributions of $ic^{*\prime}/ICM^{*}$ downwind of the 35.6 cm grid. The distributions appear to be similar. However, as shown in Fig. 3.15, they are not similar to distributions downwind of the 7.6 cm grid, which indicates that the fluctuations downwind of the 7.6 cm grid, at each y/σ, were much smaller. The cause for this marked difference is not clear. It may be partially attributed to the different positions of the sources in the two experiments. The distances from the grids to the source were $x_o/M = 20$ for the 7.6 cm grid and $x_o/M = 3.5$ for the 35.6 cm grid. It is noted, however, that the observed differences are consistent with the difference in the distributions of the intermittencies in the two cases, which has been discussed above.

Figure 3.16 shows the values of the intermittencies γ for the measurements downwind of the 35.6 cm grid and downwind of the 7.6 cm grid. It appears from the data that the distributions of γ at $x/M = 2.07$, 4.215 and 8.43 are approximately similar. The distributions of γ at $x/M = 36$ - 102 downwind of the 7.6 cm grid are also similar but much larger than those at $x/M \leq 8.4$ and give at $y/\sigma < 1$ values of γ of about 1. The measurements at $x/M = 17$ downwind of the 35.6 cm grid and those at $x/M = 20$ downwind of the 7.6 cm grid do not match each other, as expected.

Of great interest are the autocorrelation functions of the fluctuations, defined as

$$R(\tau) = \overline{ic(t)\ ic(t+\tau)}/\overline{ic(t)^2} \quad .$$

Its value for $\tau \to 0$ is always 1 and its limit for large τ is zero.

In Fig. 3.17, the distributions of R at the centerline of the plume are plotted versus the dimensionless time $\tau U/M$.

The figure demonstrates the continuous increase with distance of the characteristic time scale of the fluctuations, which is consistent with the impression portrayed by the concentration fluctuations shown in Fig. 3.2.

In Fig. 3.18 the same autocorrelations versus $\tau U/\sigma$ are plotted. The figure demonstrates a remarkable similarity of the autocorrelation function at all distances, except for a slight deviation of the correlation at $x/M = 2.07$. The similarity indicates that the time scale of the fluctuations at all distances is proportional to σ/U, namely to the time that a fluid parcel with a longitudinal dimension of σ passes a stationary point. The results also suggest that the longitudinal length scale of fluid parcels with correlated concentrations, at different distances from the source, is of the order of the local value of σ at each distance.

Similar results are obtained for the autocorrelation functions at $y/\sigma = O(1.5)$, which are shown in Figs. 3.19 and 3.20. At these values of y/σ, the correlations for both $x/M = 2.07$ and 4.215, deviate from the common similar shape of $R(\tau U/\sigma)$ at $\tau U/\sigma > 1$.

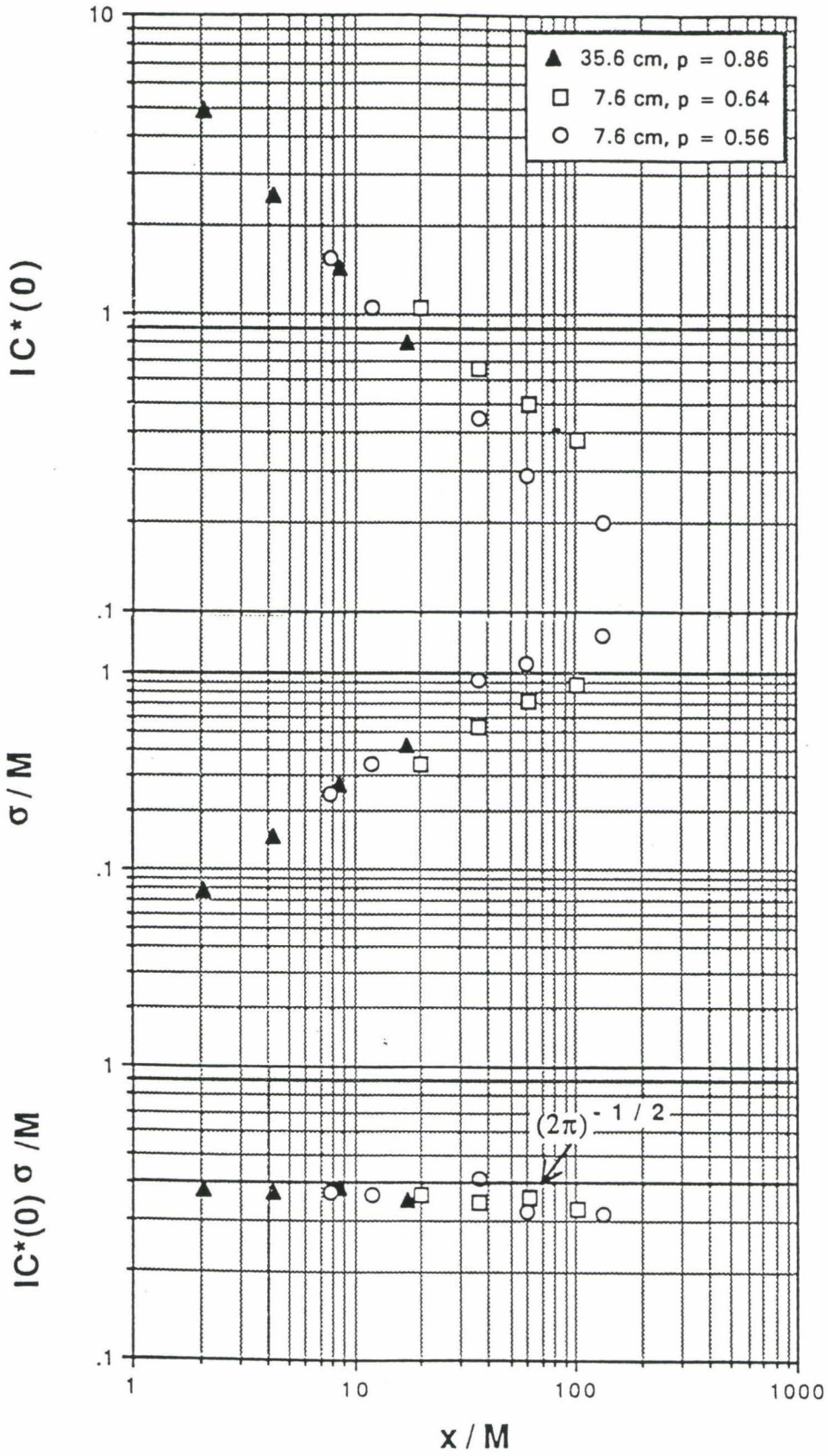

Fig. 3.1. The longitudinal variation of σ/M, $ICM^{*}(0)$ and their product for plumes diffusing in grid-generated turbulence.

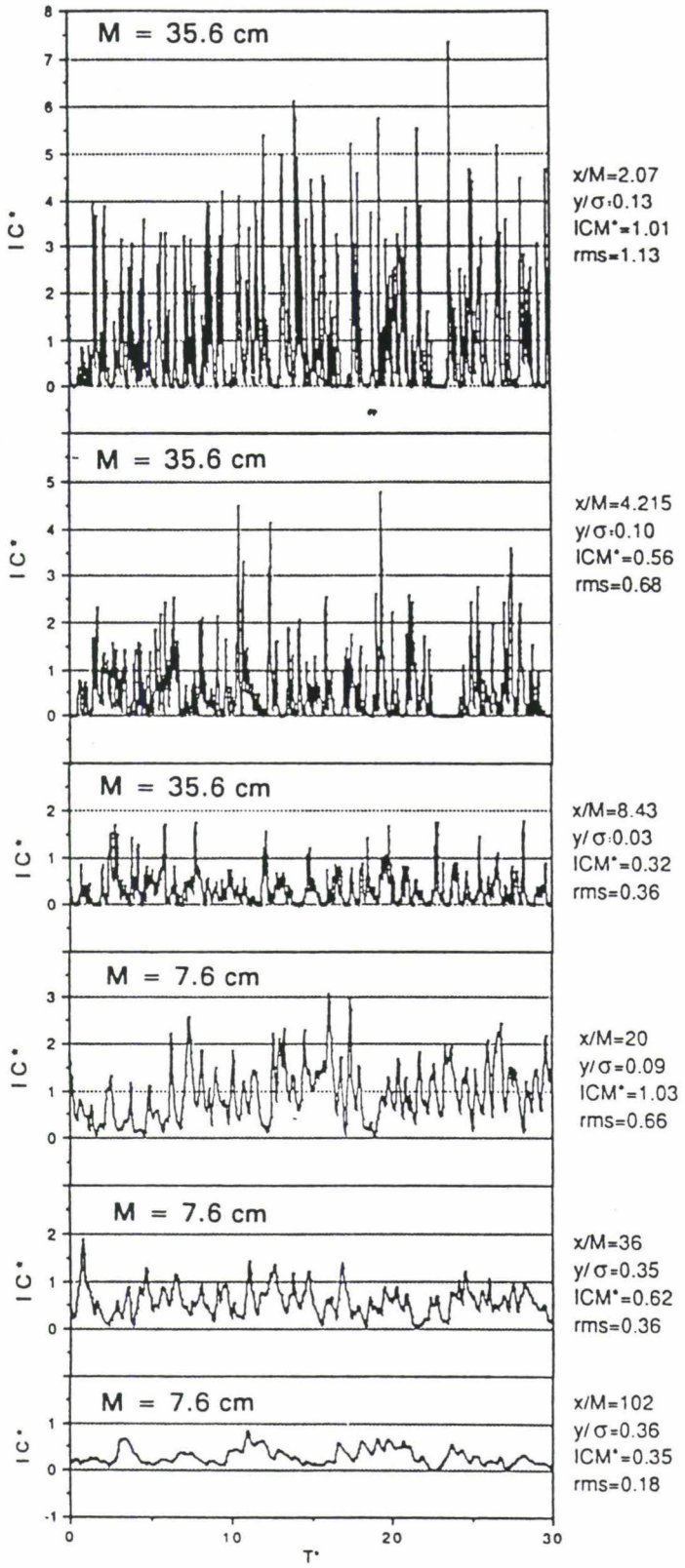

Fig. 3.2. Typical IC* fluctuations near the center of the plume at different distance downstream of the source.

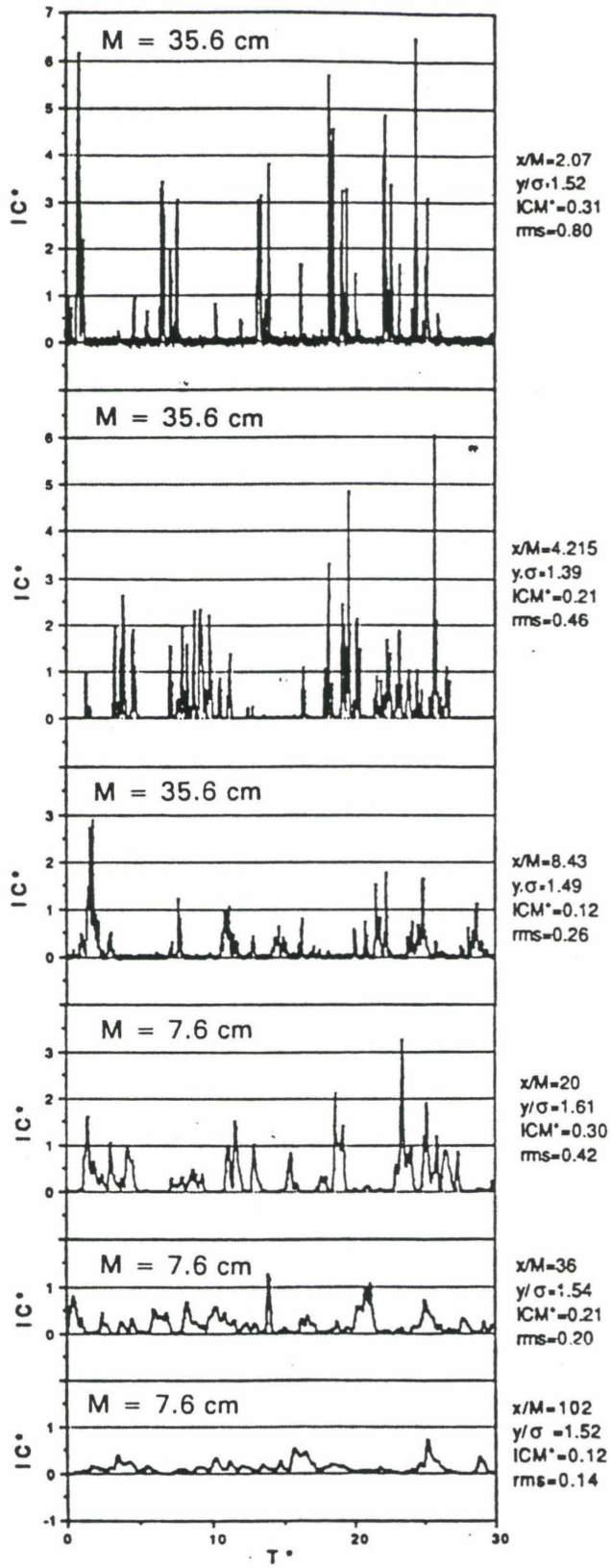

Fig. 3.3. Typical IC* fluctuations at the edge of the plume ($y/\sigma = 7.5$) at different distances downstream of the source.

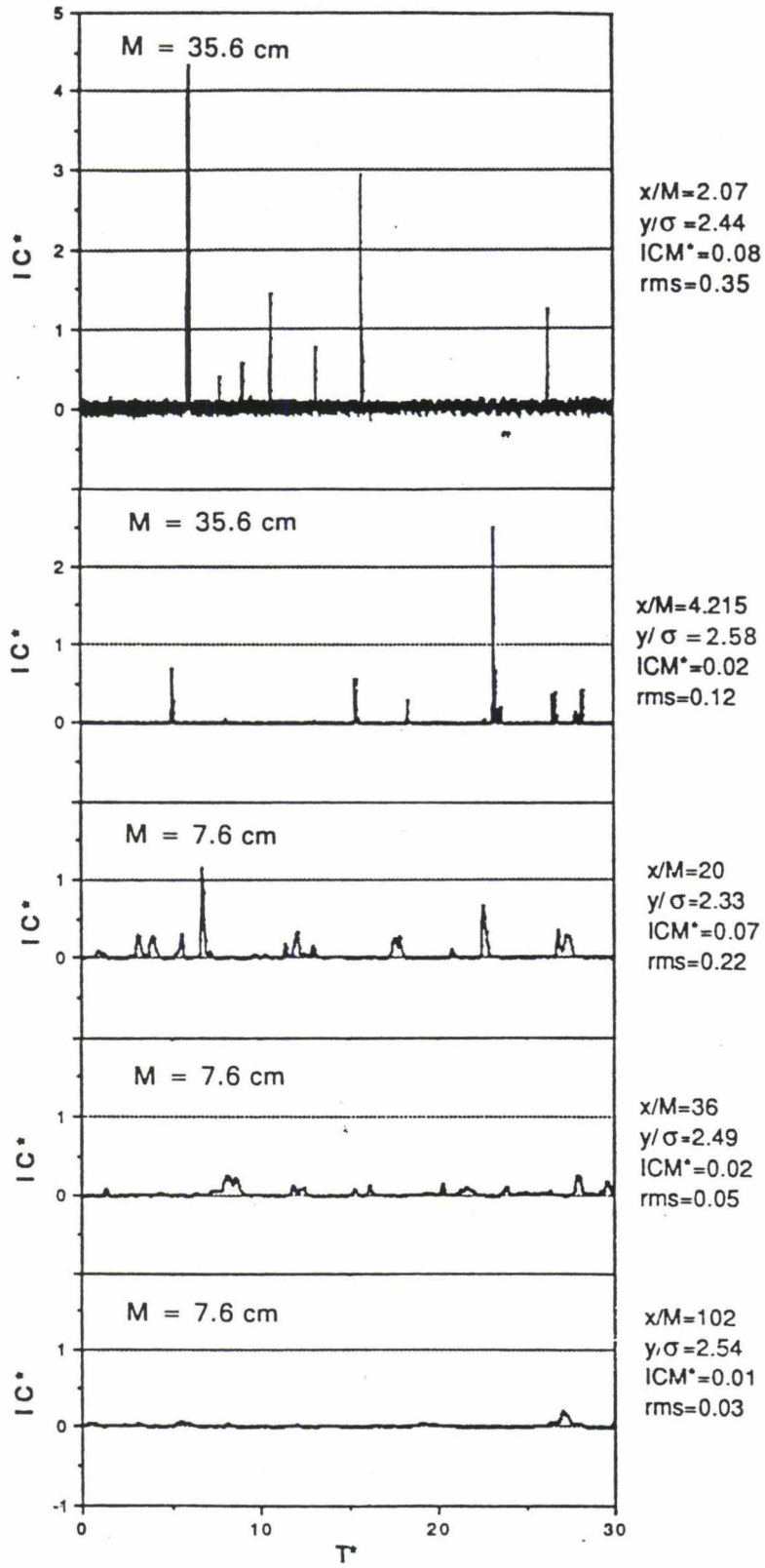

Fig. 3.4. Typical IC* fluctuations at the far edge of the plume at different distances downstream of the source.

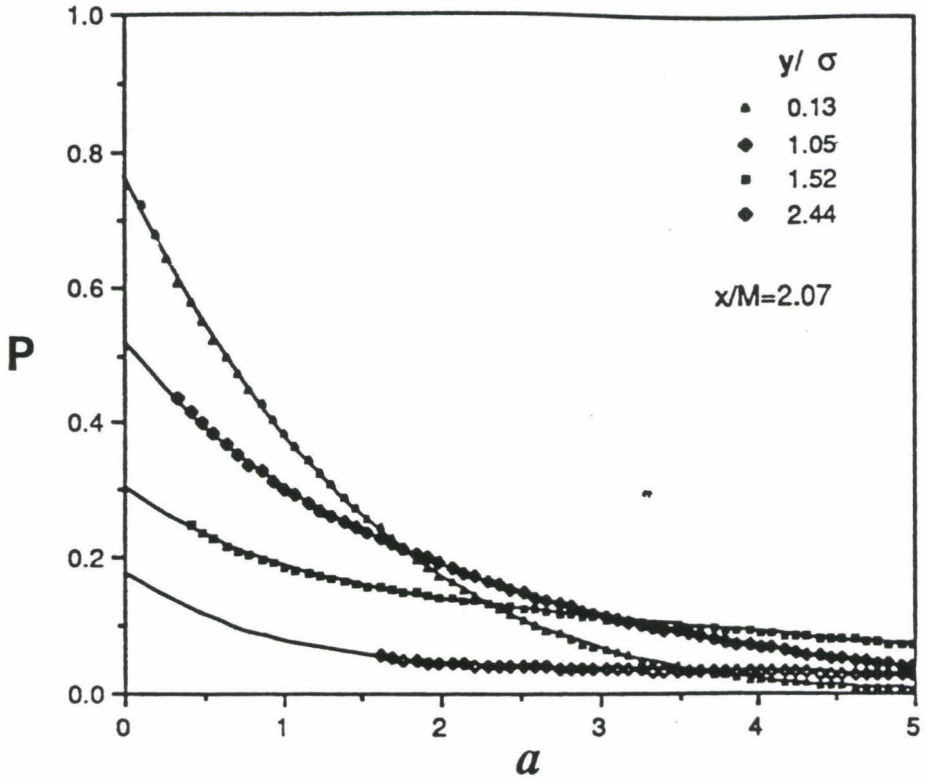

Fig. 3.5. Measured distributions of the probability P(a) that IC*/ICM* exceeds the value a, at x/M = 2.07.

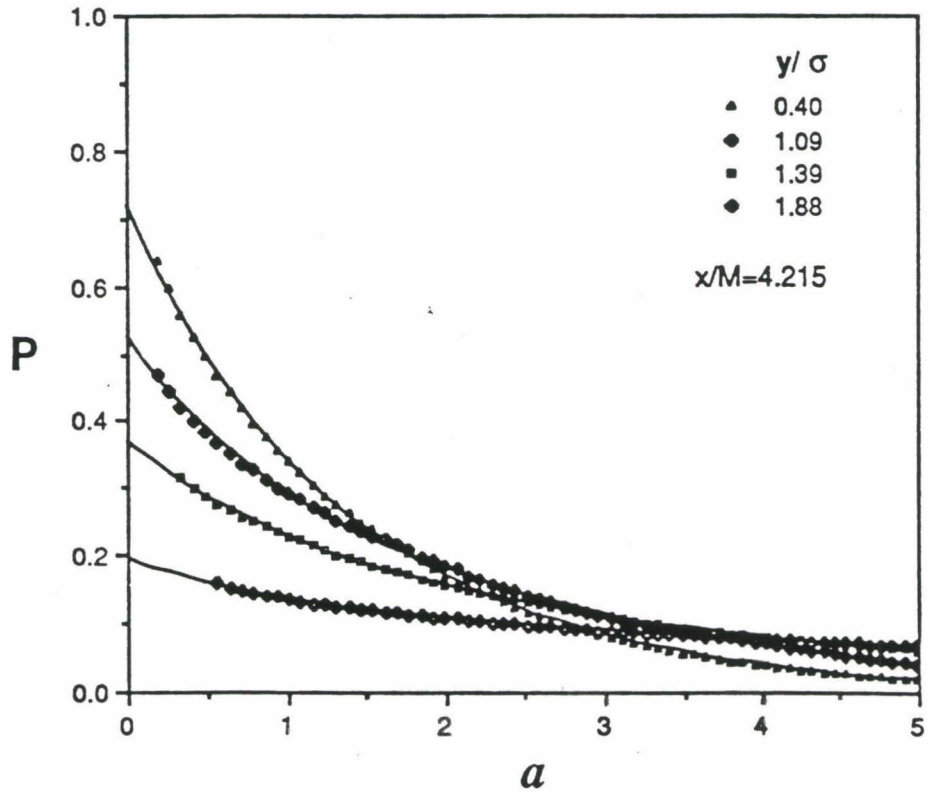

Fig. 3.6. Measured distributions of the probability P(a) that IC*/ICM* exceeds the value a, at x/M = 4.215.

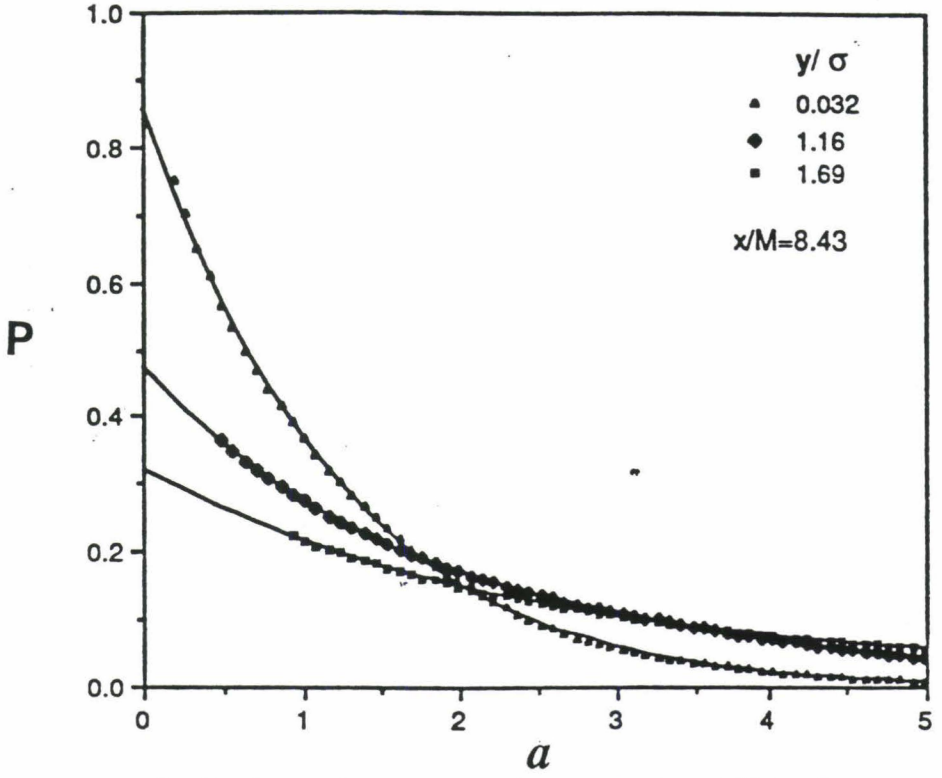

Fig. 3.7. Measured distributions of the probability P(a) that IC*/ICM* exceeds the value a, at x/M = 8.43.

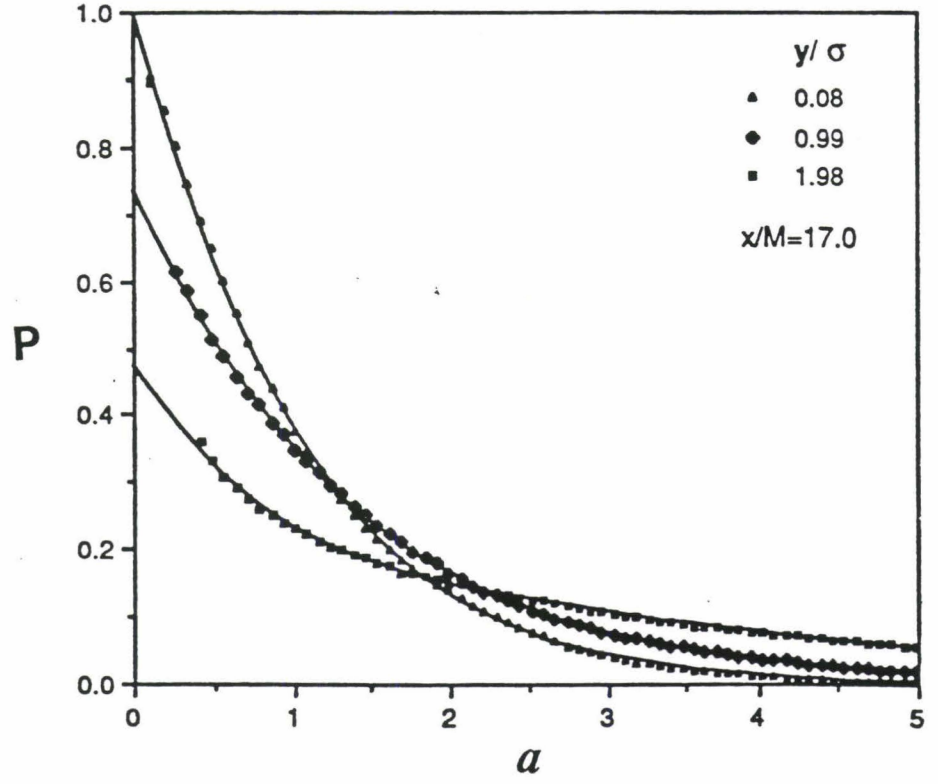

Fig. 3.8. Measured distributions of the probability P(a) that IC*/ICM* exceeds the value a, at x/M = 17.0.

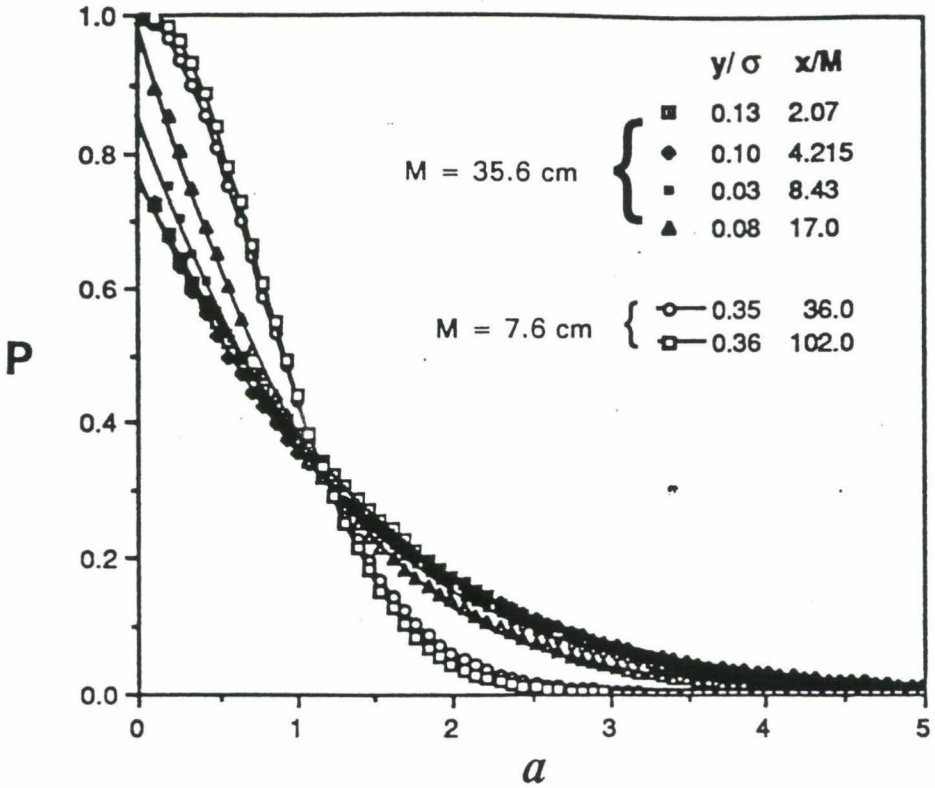

Fig. 3.9. Typical distributions of the probability P(a) that IC*/ICM* exceeds the value a near the centerline of the plume at different distances from the source.

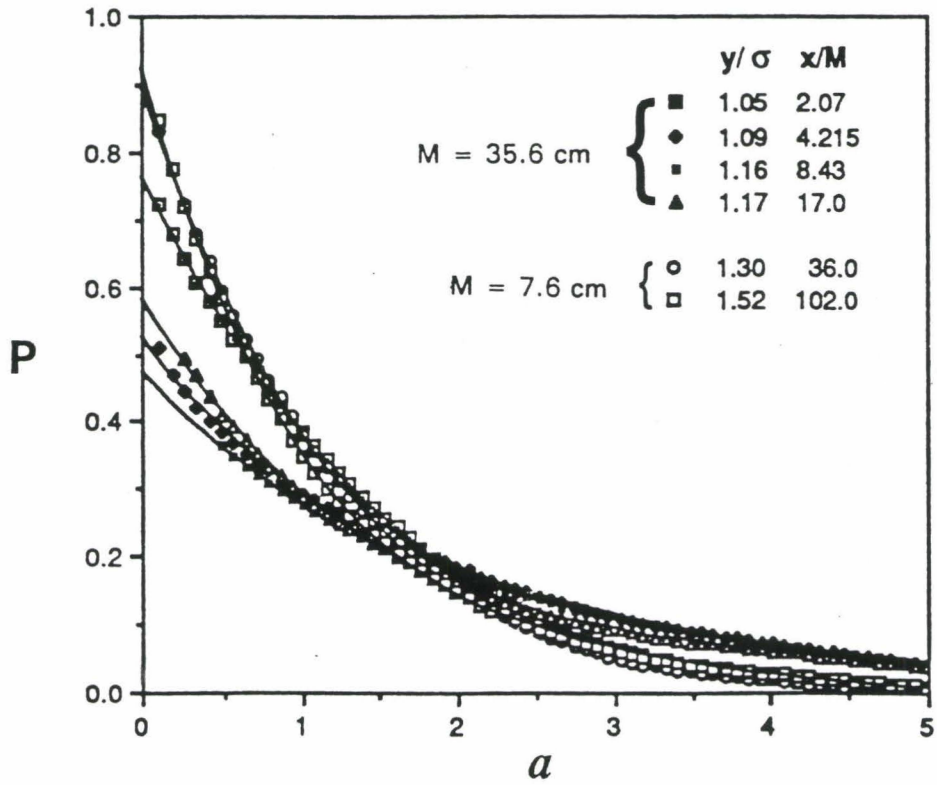

Fig. 3.10. Typical distributions of the probability P(a) that IC*/ICM* exceeds the value a around y/σ = O(1) at different distances from the source.

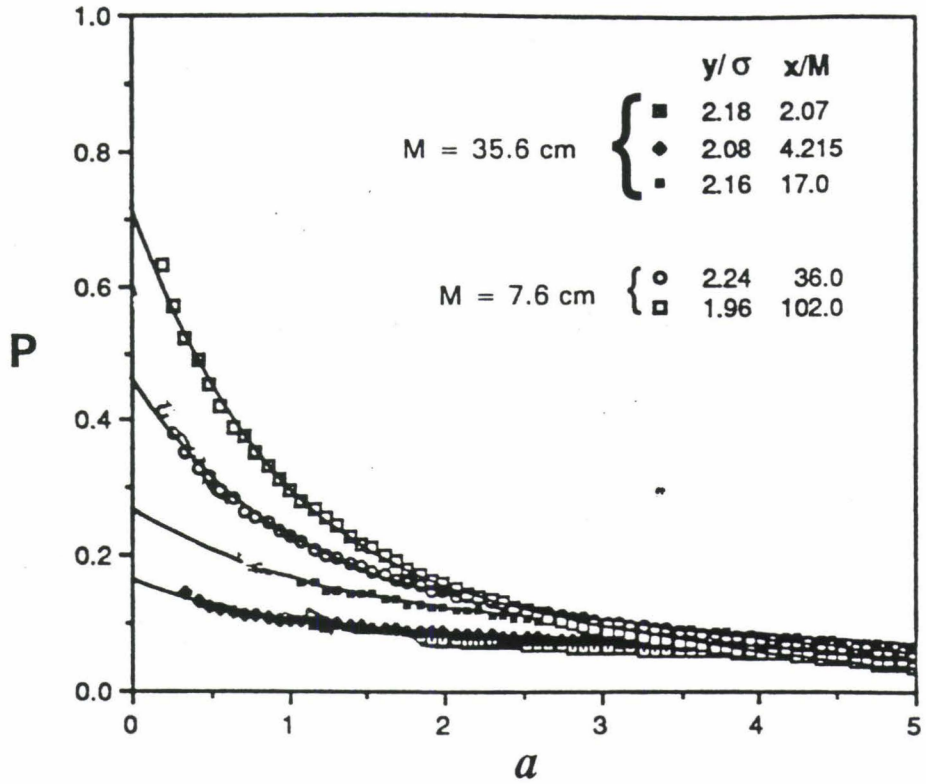

Fig. 3.11. Typical distributions of the probability P(a) that IC*/ICM* exceeds the value a around y/σ = O(2.0) at different distances from the source.

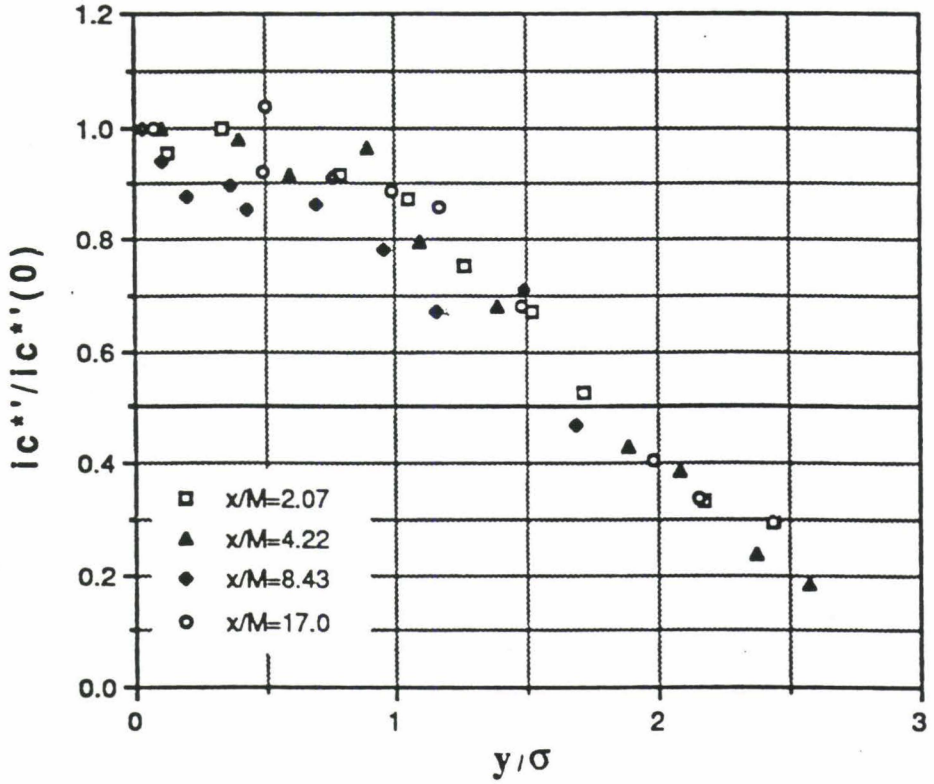

Fig. 3.12. The lateral distributions of the ic*'/ic*'(0) at different x/M downwind of the 35.6 cm grid.

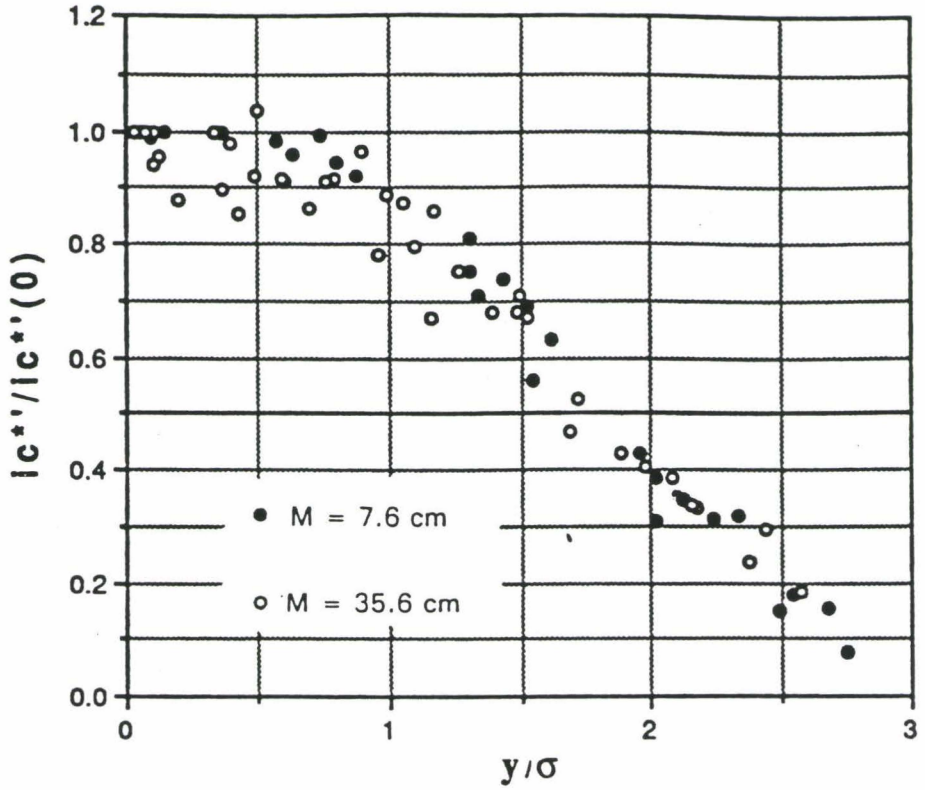

Fig. 3.13. Comparison of the lateral distributions of $ic^{*\prime}/ic^{*\prime}(0)$ downwind of the 35.6 cm grid ($x/M \leq 17$) and the 7.6 cm grid ($x/M \geq 20$).

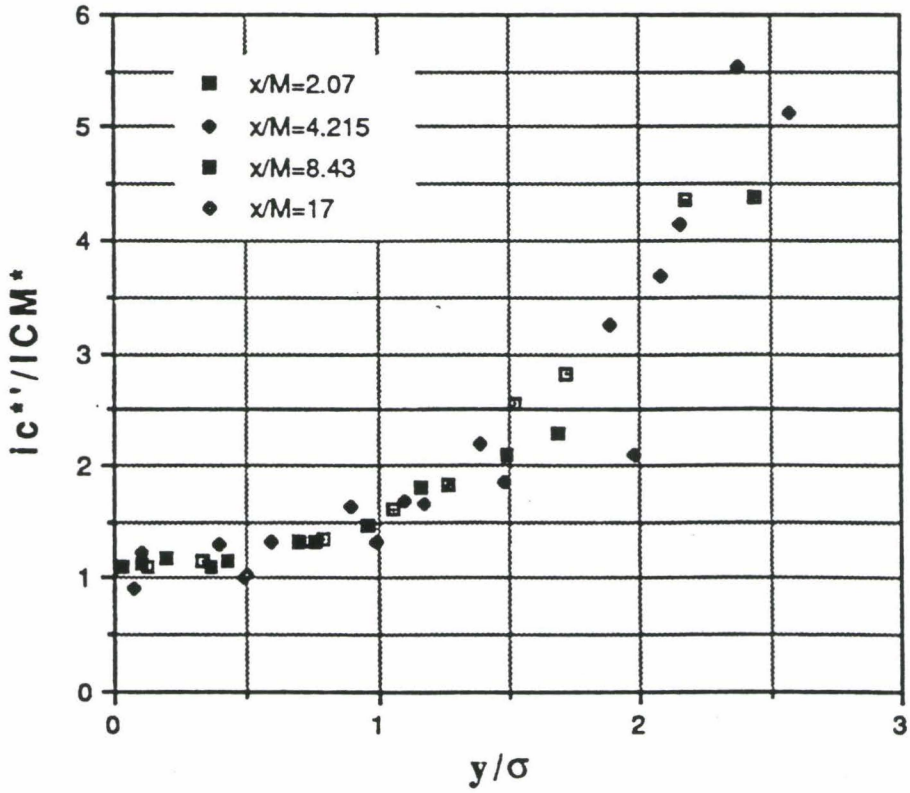

Fig. 3.14. Lateral distribution of the rms value of IC^{*} relative to its local mean value downwind of the 35.6 cm grid.

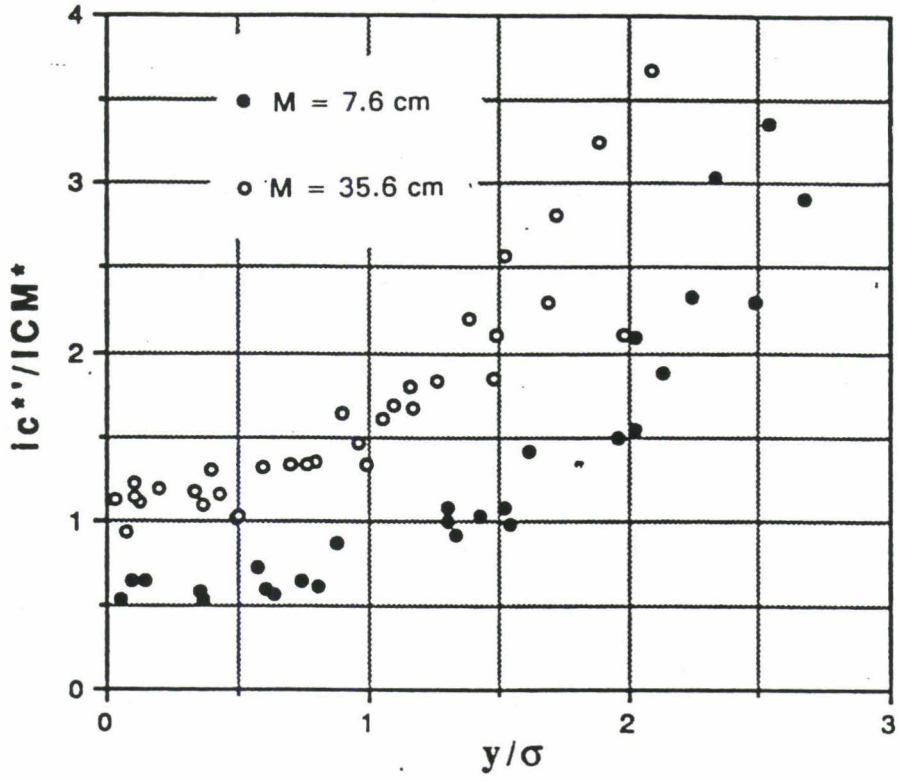

Fig. 3.15. Comparison of the distributions of the rms/mean values downwind of the 35.6 cm grid ($x/M \leq 17$) and downwind of the 7.6 cm grid ($x/M \geq 20$).

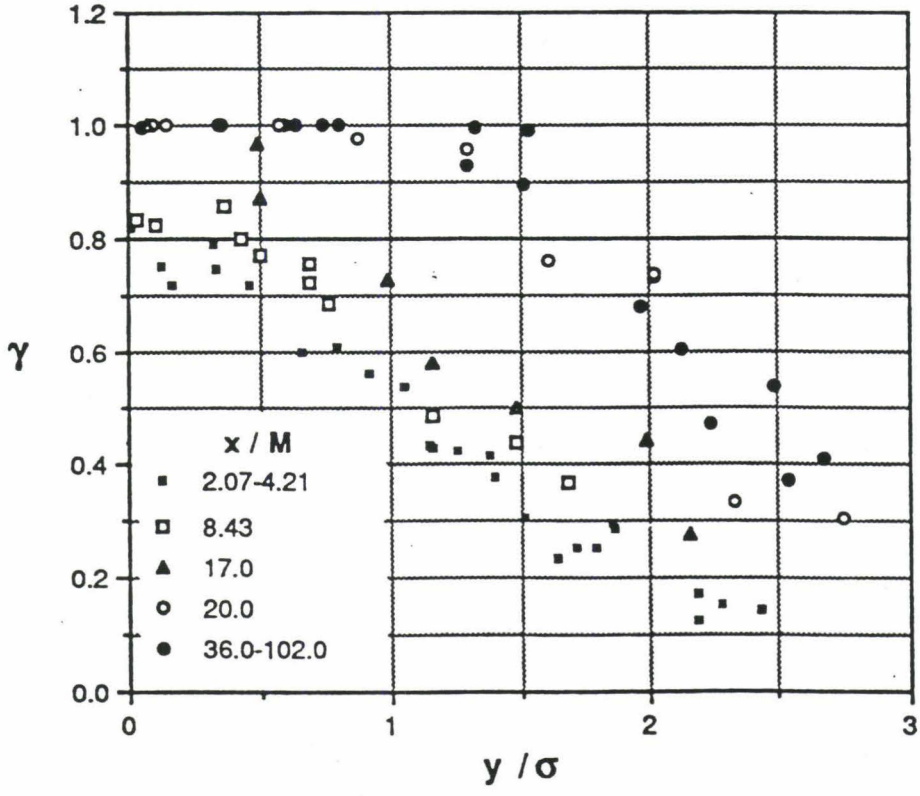

Fig. 3.16. Lateral distribution of the intermittency γ.

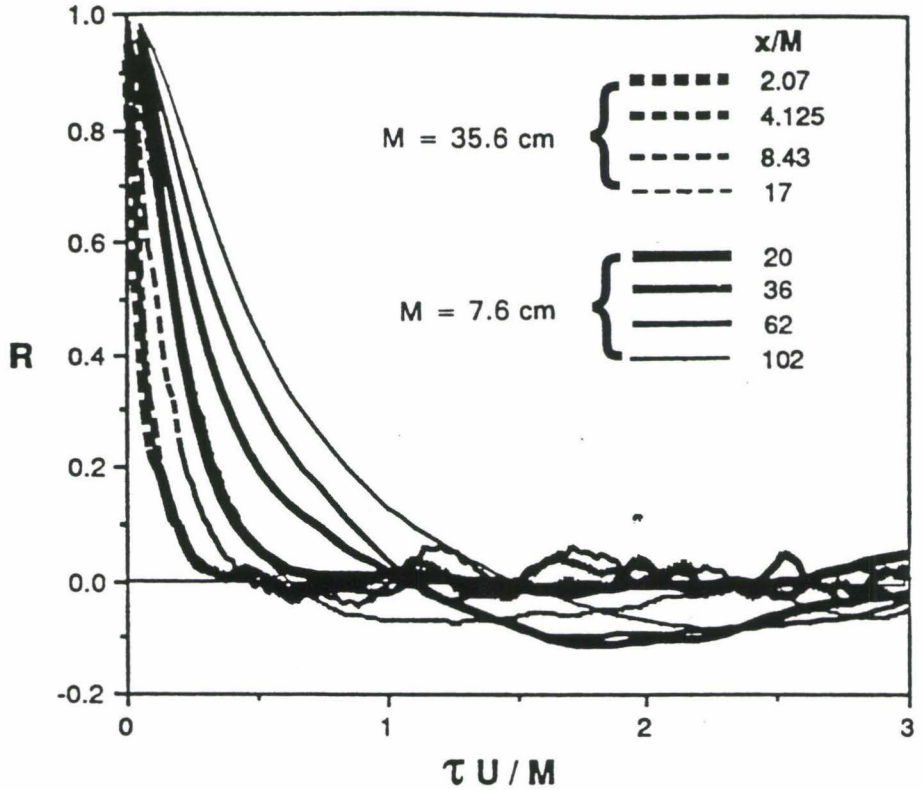

Fig. 3.17. Plot of the autocorrelation of IC* versus τU/M near the centerline of the plume.

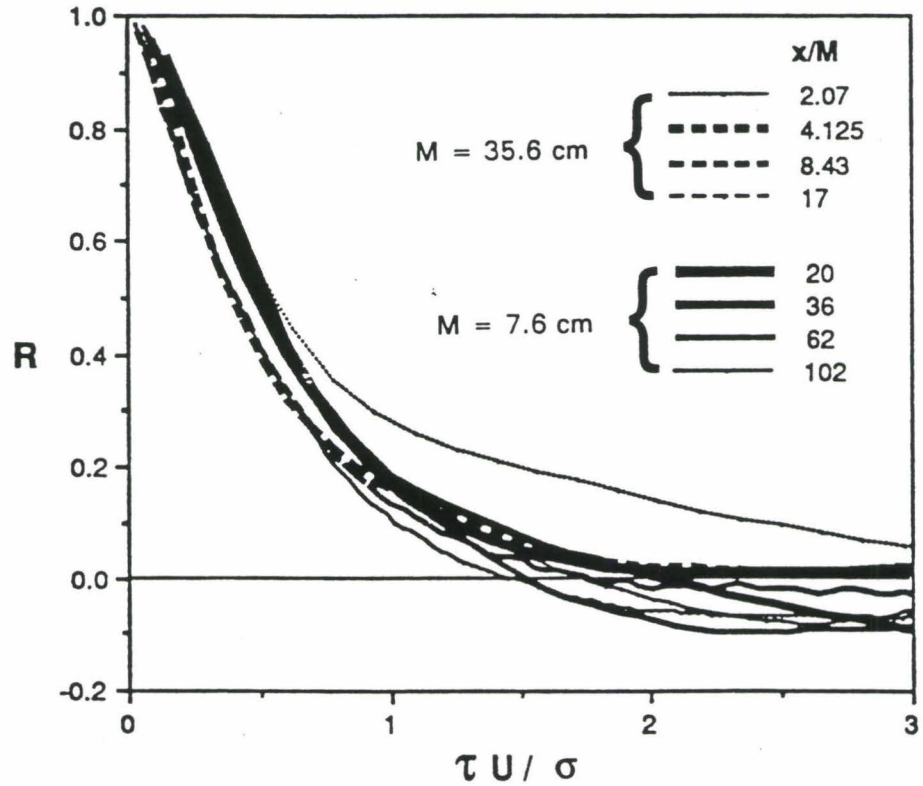

Fig. 3.18. Plot of the autocorrelation of IC* versus τU/σ near the centerline of the plume.

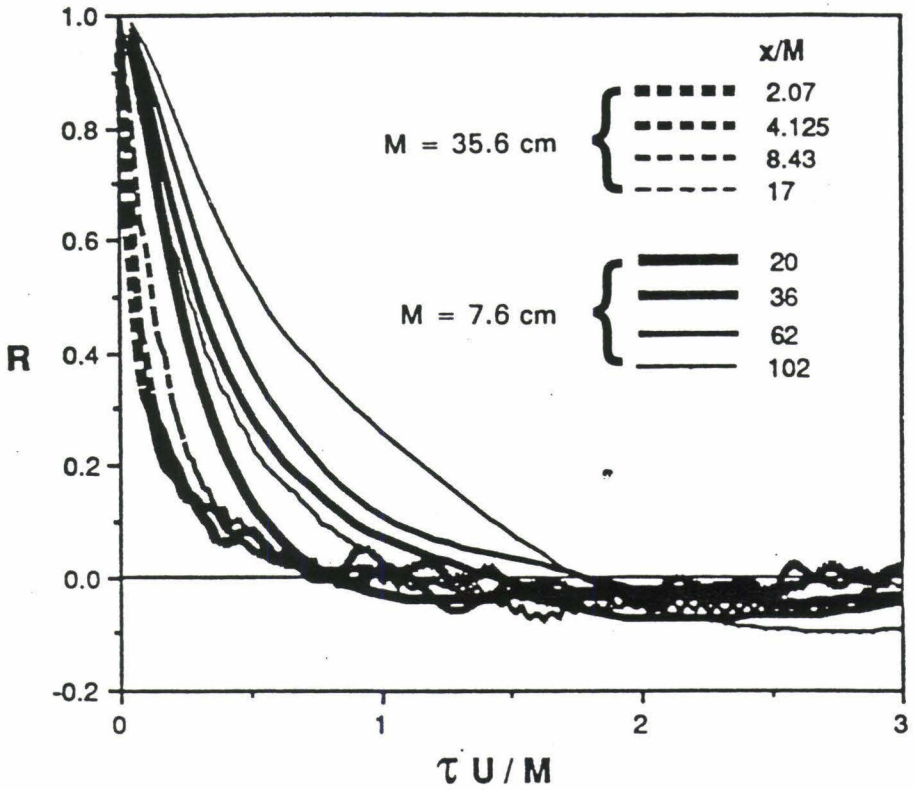

Fig. 3.19. Plot of the autocorrelation of IC* versus τU/M around y/σ = 1.5.

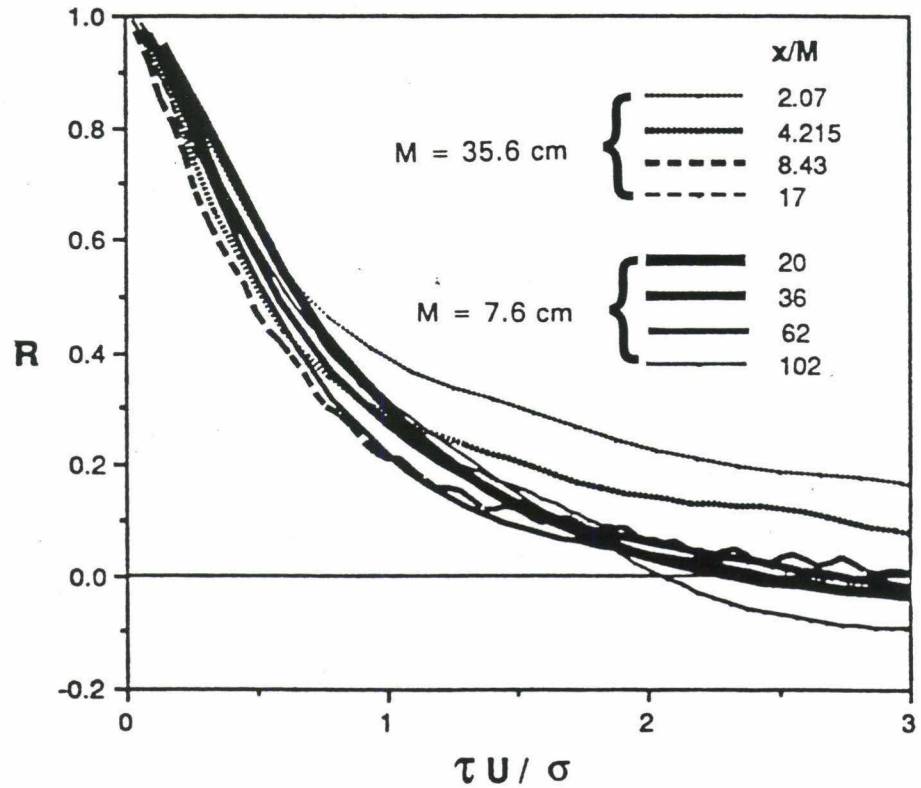

Fig. 3.20. Plot of the autocorrelation of IC* versus τU/σ around y/σ = 1.5.

4.0 DISCUSSION AND CONCLUSIONS

Measurements have been made of Integrated Concentration (IC) fluctuations across plumes diffusing from a point source in a turbulent flow generated by a 35.6 cm grid. The large size of the grid made it possible to study the characteristics of the IC fluctuations at relatively short distances from the source, $2 < x/M < 17$, where M is the size of the grid and x is the distance from the source. Particular attention was given in the analysis of the data to a possible existence of similarity of the fluctuations at different distances from the source.

Similarity of dispersing plumes in turbulent flows is defined as the existence of similar dimensionless cross-wind distributions of the statistical properties of the concentration field at different distances, which are independent of the distance from the source of the plume. For example, it is well established that the mean concentration distributions across a plume C(y) dispersing in grid-generated turbulence are similar and can be described by a dimensionless Gaussian function.

$$C/C(o) = \exp(-y^2/2\sigma^2),$$

where σ is the local lateral length scale of the plume. Both C(o) and σ are, of course, functions of the distance x from the source.

A similar dimensionless Gaussian function has also been shown to describe the lateral distributions of the mean concentration of plumes diffusing in boundary layers. However, the vertical distributions of mean concentration of such plumes are not similar and deviate considerably from the Gaussian shape (Pasquill, 1974, pp. 204-205).

Clearly, different levels of similarity may exist, from a similarity which is limited to the mean values of the concentration field, to a similarity of all the statistical properties of the fluctuating concentration field.

The existence and the level of similarity is of great theoretical and practical significance. Its theoretical significance is that it exhibits a moving equilibrium of the flow or the diffusing plume, in which the conditions upstream are mostly irrelevant, so that dimensionless distributions based on local velocity and length scales are similar or self preserving. (See Townsend, 1956.) It also indicates that the various turbulent processes, which are expressed by the various terms in the equation for the mean and fluctuating quantities, are in equilibrium. The practical importance of the existence of similar or approximately similar plume characteristics is that it permits formulation of simple prediction models. The advantage of such models is so great that the (similar) Gaussian model has been adopted for use in most air-pollution models, even though it is well recognized that the vertical mean concentration distributions in most cases are not Gaussian and depend on the distance from the source.

As indicated earlier, the existence of similar lateral Gaussian mean concentration profiles across plumes diffusion in both grid-generated turbulence does not imply a higher level of similarity of the statistical properties of concentration fluctuation.

When analyzing the dynamics of plumes diffusing in turbulent flow, one distinguishes between an instantaneous plume (typical lateral length scale σ_i) and a mean plume (typical length scale σ). The fluctuations of the concentrations at a point are viewed to be a result of the meandering of the instantaneous plume and the concentration fluctuations within the instantaneous plume (in-plume fluctuations). A similarity of concentration fluctuations within a certain range would imply that the ratio σ_i/σ remains constant within that range. Theoretical

considerations (Hinze, 1975) suggest that σ_i and σ grow at different rates at different distances from the source, and that the relative role of the meandering reduces with the distance. Very close to the source, at least for ideally small sources, the fluctuations are primarily due to meandering caused by relatively large eddies. At very large distances, on the other hand, when the size of the instantaneous source becomes larger than that of the turbulent eddies in the flow, the effect of meandering decreases, the ratio σ_i/σ approaches one, and the relative magnitude of the fluctuations decrease.

Indeed, the measurements reported herein are consistent with such a model. The measured distribution of γ, which designates the portion of the time at which the plume crosses the line of concentration integration, are smaller at small distances from the source. As seen from Fig. 3.16, the value of γ at the center of the plume in the range $2 < x/M < 4$ is about 0.75. Namely, for 25% of the time the entire plume was at either side of the line of concentration integration. At large distances from the source, $x/M > 20$, γ was 1 at the entire central region of the mean plume, $-1.0 < y/\sigma < 1.0$, and intermittency due to meandering was noticed only at the edges of the plume. Clearly, this observation indicates that the fluctuations near the source are primarily due to the meandering of the instantaneous plume. It also indicates that the average ratio of σ_i/σ increases with the distance from the source and stays approximately constant at $20 < x/M < 100$. The physical reason for this type of development is the following: The growth of σ is controlled by the energy of all the eddies in the flow, whereas the growth of σ_i is due to eddies of sizes approximately equal to or smaller than the size of the instantaneous plume, which is of the order of 2 σ_i. Initially $\sigma_i << \sigma$, but when σ_i becomes large and closer to σ, its growth rate becomes close to that of σ.

Now, in spite of the lack of similarity of the probability density distributions of the IC fluctuations, the measurements exhibit a universal similarity of a few functions of the fluctuations. First, as indicated earlier, the distributions of the mean values ICM(y), are always similar and can be described by a Gaussian distribution (Eq. 3.3). Then, the distributions of the rms of the fluctuations at all stations appear to be similar (Fig. 3.13). On the other hand, the distributions of the ratio of the rms to the mean, in the range $x/M < 20$ downwind of the 35.6 cm grid and in the range $x/M \geq 20$ downwind of the 7.6 cm screen, are not similar, although for each range, a similarity of $ic^{*\prime}/ICM$ was found. This finding (Fig. 3.15) supports our previous conclusion that at $x/M < 20$, some of the instantaneous plumes are close to or have already reached the size of the mean plume. Thus, they increase the mean value of IC without contributing to the rms of the fluctuations.

It was also surprising to find that in spite of the absence of similarity, the autocorrelations at all stations, except very very close to the source, were proportional to the local length scale σ and similar to each other (Figs. 3.18 and 3.20). Since $R(\tau)$ is based on the correlation of the fluctuations, namely the deviations from the mean, the result is consistent with the existence of similarity of the rms values of the fluctuations.

Previously it was concluded that the autocorrelation curves suggest that the instantaneous plume disintegrates into patches with relatively high concentrations separated by entrained air with zero or small concentrations. The similar autocorrelation curves indicate that these patches pass a given line normal to the flow within a period of the order of $2\sigma/U$, at all distances from the sources, although the typical "width" of the instantaneous plume is relatively smaller at small distances from the source. This observation also suggests that the breakup of the instantaneous plume is by relatively large eddies, which also determine the meandering of

the plume and its mean size. The dominant role of the large eddies in determining the meandering and the breakup of the instantaneous plume and its diffusion, is probably the reason for the similarity between the fluctuations of the Vertical Integrated Concentration across plumes diffusing in a boundary layer flow and the fluctuations of IC across plumes diffusion in grid-generated turbulence.

Clearly, the investigation has yielded a detailed view of both the dispersion process and the characteristics of the fluctuations of integrated concentrations across plumes. Hopefully a relatively simple model can be developed, using data collected in the project, which would describe the dynamics of plumes diffusing in different types of flows.

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